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Second Quarterly Report

on

Stabilized CO_2 Gas Laser

(1 March 1967 - 1 June 1967)

Contract No. NAS5-10309

Prepared by

Sylvania Electronic Systems
Western Operation
Mountain View, California

for

Goddard Space Flight Center
Greenbelt, Maryland

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Approved by

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Greenbelt, Maryland

FOREWORD

This report is the second quarterly engineering report summarizing the work performed under NASA Contract NAS5-10309 entitled "Stabilized CO_2 Gas Laser," covering the period 1 March 1967 to 1 June 1967. This report was prepared by the Advanced Technology Laboratory of Sylvania Electronic Systems - Western Operation, Mountain View, California. It describes work performed in the Quantum Electronic Devices Department, headed by Mr. Mahlon B. Fisher. Mr. Richard S. Reynolds is the principal investigator on the program. Other contributors to this report are Dr. J. D. Foster and Mr. D. Revall.

All the work performed under this contract was administered by the Optics Branch, NASA-Goddard Space Flight Center, Greenbelt, Maryland. Mr. N. McAvoy is the principal technical representative for the Optics Branch.

ABSTRACT

Design, fabrication and testing were continued during this quarter toward the development of a sealed-off, 20-watt, stabilized single-frequency CO_2 laser. This report describes (1) the efforts toward obtainment of single-mode operation in the laser with maximum output power, (2) the amplifier gain studies, (3) the thermal stability measurements of the laser cavity, (4) the mechanical design of the oscillator-amplifier package and (5) the thermal control and AFC electronics completed this quarter.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

1.0 INTRODUCTION

The objective of this program is to develop a frequency-stabilized, high-power, sealed-off CO_2 laser suitable for use in a coherent optical communications system operating at 10.6 microns. The details of the program objective and the techniques to be used were given in the First Quarterly Report covering the period 1 December 1966 to 1 March 1967. During that period, the oscillator portion of the oscillator-amplifier chain was designed and constructed. Testing of various laser tubes started during the first quarter and have continued this quarter. Preliminary short-term stability and resonant frequency tests were performed during the last quarter and it appeared the cavity design would be adequate for obtaining a short-term frequency stability of 1 part in 10^{10}.

The early stability measurements were made at a wavelength of 0.6328 microns. During this quarter they have been extended to the 10.6 micron case and have revealed information on the long-term stability of the laser cavity.

The thermal control system and the AFC electronics designed during the last quarter were fabricated during this quarter. Description of these components is given in the following sections along with a discussion of the various studies made this quarter, which include parametric measurements on R.F. excited oscillators and amplifiers, color center formation in salt Brewster windows and lifetime tests on both d.c. and R.F. tubes.

2.0 TECHNICAL DISCUSSION

2.1 20-Watt Laser Design

As discussed in the First Quarterly Report, we have chosen an oscillator-amplifier approach in order to obtain a 20-watt laser output simultaneously with very good frequency stability ($1:10^{10}$). Both the oscillator and amplifier will be mounted on a tracking telescope which ultimately will be used to track a satellite. Precise optical alignment between the oscillator and amplifier, and between the entire unit and the rest of the optical system must be maintained for orientations ranging from vertical to horizontal.

Extremely rigid mounting techniques, however, are not desirable because of the induced excellent coupling of the telescope mechanical vibrations to the laser oscillator creating unwanted laser frequency instabilities. The amplifier, not contributing significant frequency instabilities to the laser beam through vibrations, can be rigidly mounted to the telescope.

Fortunately, for the case of 10 micron radiation, some relaxation of the angular mounting tolerance can be realized over systems which operate in the visible portion of the spectrum. The approximately 20 fold increase in wavelength results in a substantial increase in the angular diffraction limit for the small diameter optics used in the transmitter system, and, for the optics which are used, an overall mechanical stability of $\pm$ 1.5 arc minutes at the laser will be sufficient to maintain diffraction limited operation for the entire system.

Therefore, as a compromise between absolute mechanical rigidity and freedom of vibrational influences a design has been developed which allows a controlled, semi-rigid mounting structure for the laser oscillator only, while the rest of the laser system maintains a rigid mounting.

As described in the first quarterly, the laser oscillator in itself is mechanically very rigid. The mirror and laser tube mounting structures are all designed to tightly clamp their respective components after alignment so that no degradation in operating characteristics can occur for any orientation. The purpose of this design is not only to insure operation in all orientations but also to maintain as high a mechanical resonant frequency as possible in the laser structure. This is necessary in order to reduce the possible effects of the low frequency, large amplitude acoustic vibrations which are present in a normal environment.

Figure 1 is an assembly drawing of the laser oscillator-amplifier combination. A 12 inch wide by 48 inch long channel is used to provide a mounting platform for the oscillator, amplifier and auxiliary optics. In this figure only one amplifier tube is shown. A second amplifier can be mounted directly above the first. Each amplifier is mounted in its own lightweight channel which extends approximately 43 inches beyond the main enclosure. The overall length of the entire unit will be approximately 91 inches. The region above the oscillator is reserved for additional electronics, ballast resistors, etc..

As indicated in Figure 1, the support mechanism for the oscillator consists of a series of taught wires so arranged so as to clamp the laser with any desired force to a set of laminated pads attached to the bottom of the 12 inch channel. These pads designed for acoustic isolation will be constructed with layers ofmetal and semi-flexible acoustic dampening material which can be compressed to the desired rigidity. This technique allows the oscillator to be mounted <u>only</u> as rigidly as necessary to obtain the required $\pm$ 1.5 minutes of arc stability for any orientation.

In order to reduce the intensity of air born acoustic waves reaching the laser oscillator, the entire inside covers and base of the laser enclosure will be covered with several layers of type Y-9052 industrial vibration damping material made by 3 M Company. This material is a pressure-sensitive,

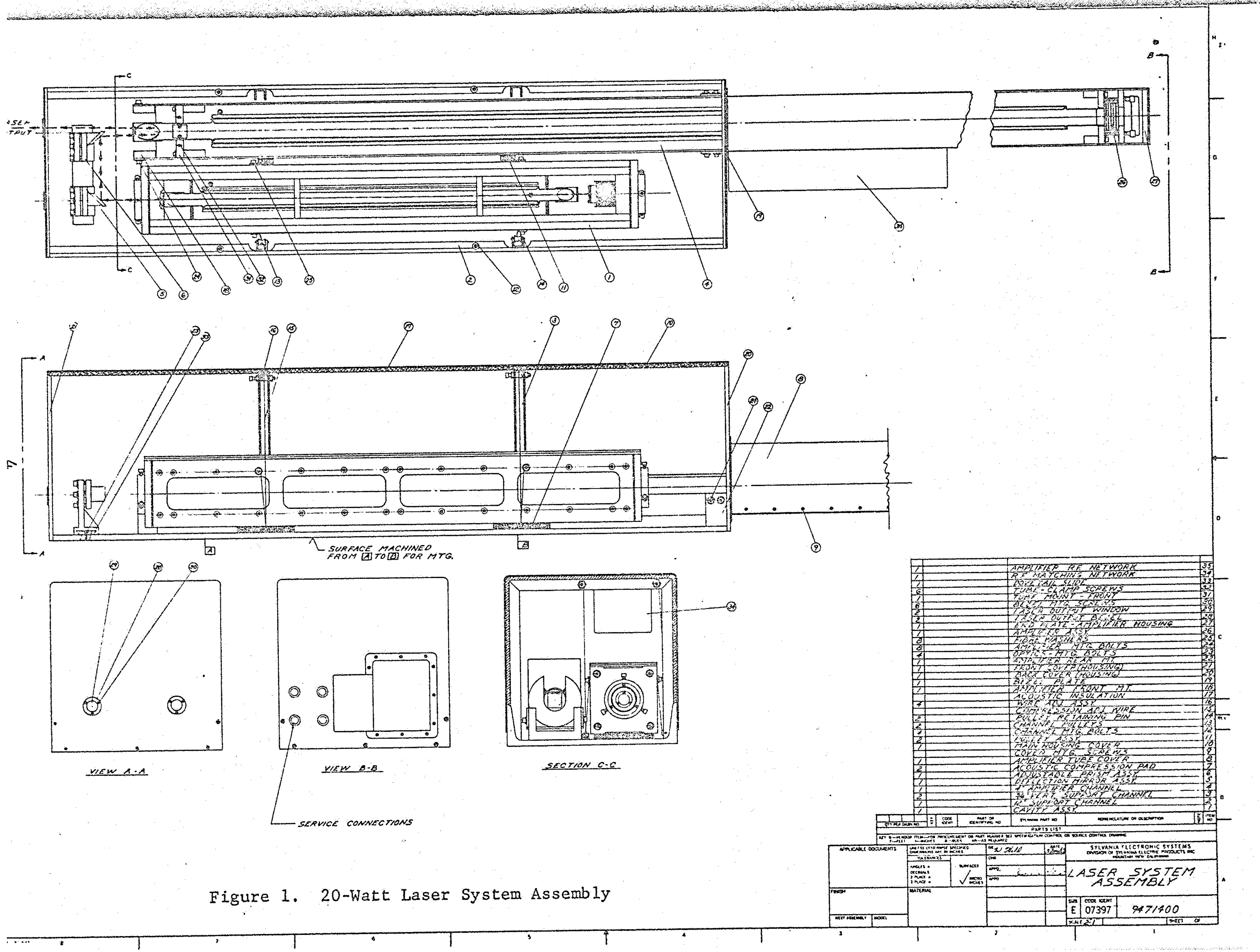

Figure 1. 20-Watt Laser System Assembly

specially compounded polyurethane acoustic damping foam with an aluminum foil paper laminant constraining layer backing. The laminant structure is especially effective for vibration isolation and it also serves as an effective thermal shield to help maintain a uniform and controllable temperature within the laser enclosure.

Liquid cooling and electrical service connections will be made at the back of the unit. The entire enclosure will be temperature stabilized by the heater and temperature controller used with the laser cavity.

The laser oscillator output beam is folded and introduced through a Brewster window into the first amplifier tube slightly off axis. The laser beam is double passed through the amplifier tube, by a folding mirror at the end of the amplifier. This folding mirror focuses the beam near the input end of the amplifier so that the beam can be adjusted to miss the 45^{o} mirror. For a one amplifier system the beam can be passed out of the enclosure. For a two amplifier system, the beam is introduced into the second amplifier by a similar technique.

Two laser enclosures including the 12 inch channel, end plates, wire support brackets, and outside enclosure were fabricated this quarter. Experiments will be performed using the two laser oscillators mounted inside the enclosure to determine the overall short-and long-term stabilities to be expected. These experiments have recently started and will continue through the next quarter.

2.2 R.F. Excited Laser Tubes

Early in this quarter several studies were made on R.F. driven tubes to determine the optimum operating conditions for the lasers. As described in an earlier report, R.F. excitation was chosen for the possibility of increasing the operating lifetime of the laser. In this section, some lifetime data taken this period is reported and studies made on the phenomenum of "coloring" of salt Brewster windows are discussed. Some parametric data on the power output as a function of gas composition for a particular CO_2 laser geometry is also presented.

2.2.1 Parametric Studies

A brewster angle CO_2 laser with a bore diameter of 19 mm and an active length of 65 cm was operated with R.F. excitation. Strip electrodes were laid lengthwise along both sides of the cooling jacket. The electrode separation was approximately 32 mm. Several electrode widths from 1/8 inch to 1/2 inch were tried with very similar results in all cases. The laser was cooled by a low viscosity (1.5 centistokes) silicone fluid available from Dow Corning (DC 200). The wall temperature was maintained at about $20^{o}C$. A balanced line matching network was used to match the 50 ohm output of the 27 MHz oscillator to the tube impedance. Except when operating at the low power extremes of the transmitter, a VSWR of better than 1.2 was obtained.

The laser utilized KCl Brewster windows polished flat to better the $1/10\ \lambda$ at 10 microns. The optical cavity was formed by a 3 meter radius gold-coated mirror and an Irtran 2 multilayer dielectric mirror with a 15% transmission figure. The output mirror was anti-reflection-coated. The mirrors were mounted on an optical bench rather than in a stable cavity for convenience, and the tube was allowed to run multimode.

Figure 2 is a graph of the output power from the laser as a function of gas pressure and composition. Only CO_2 and He mixtures were used, however, the addition of about 1 torr of N_2 increased the output by about 30% in most cases. This value is a much lower figure than we have observed in flowing systems where 100% increase is not unusual.

For the case of the 1/2 torr CO_2 pressure, helium was added beyond the point indicated on the graph in order to find the point at which oscillation would cease. At a total pressure of 40 torr oscillation could no longer be detected and the discharge in the tube was barely visible. At slightly higher pressures, the discharge could not be maintained. It is expected that higher pressures could be utilized with greater power supply capability.

In all cases, the output power was peaked by adjusting the input power. Generally at the lower helium pressures, the input power could be about 60-100 watts and as more helium was added the required input power rose until the maximum of 200 watts available was reached. It appears that higher powers could be reached at higher pressures with greater power supply capability, although the efficiency may be degraded somewhat.

The data in the graph of Figure 2 was taken by adding the helium to the operating laser through a high vacuum valve from a helium reservoir. At the lower pressure values, the power output from the laser would immediately rise when more helium was added and then settle back to its equilibrium value after a few minutes of operation. However, at the higher pressure values, above about 6 torr of helium, the output of the laser would decrease by about 50% and then slowly come to its equilibrium value. At the highest pressures, the time constant for the process was about 1/2 hour. This very long time constant is apparently due to the slow diffusion rate of the pure helium through the CO_2:He mixture.

2.2.2 Window Coloring Effects

The Brewster window material we have been using in the present lasers has been single crystal potassium chloride available from Harshaw Chemical. Normally these windows are quite transparent in the visible as well as the 10 micron region and appear clear to the eye. However, after operating on a laser tube after a period of time, the inside surface of the windows take on a bluish tint and when the input power to the laser is high, the windows can become very dark. A noticeable effect on the power output of the laser is also observed when the windows become dark blue.

The coloring effect is much more pronounced in the R.F. excited tubes than in the d.c. excited tubes. In a matter of only a few minutes after turn-on, the windows become noticeably colored when the R.F. lasers are operated at an R.F. power level of about 200 watts. Within an hour after turn-on, the laser windows are very dark and the output power begins to decrease. Maximum power reductions of about 25% have been observed.

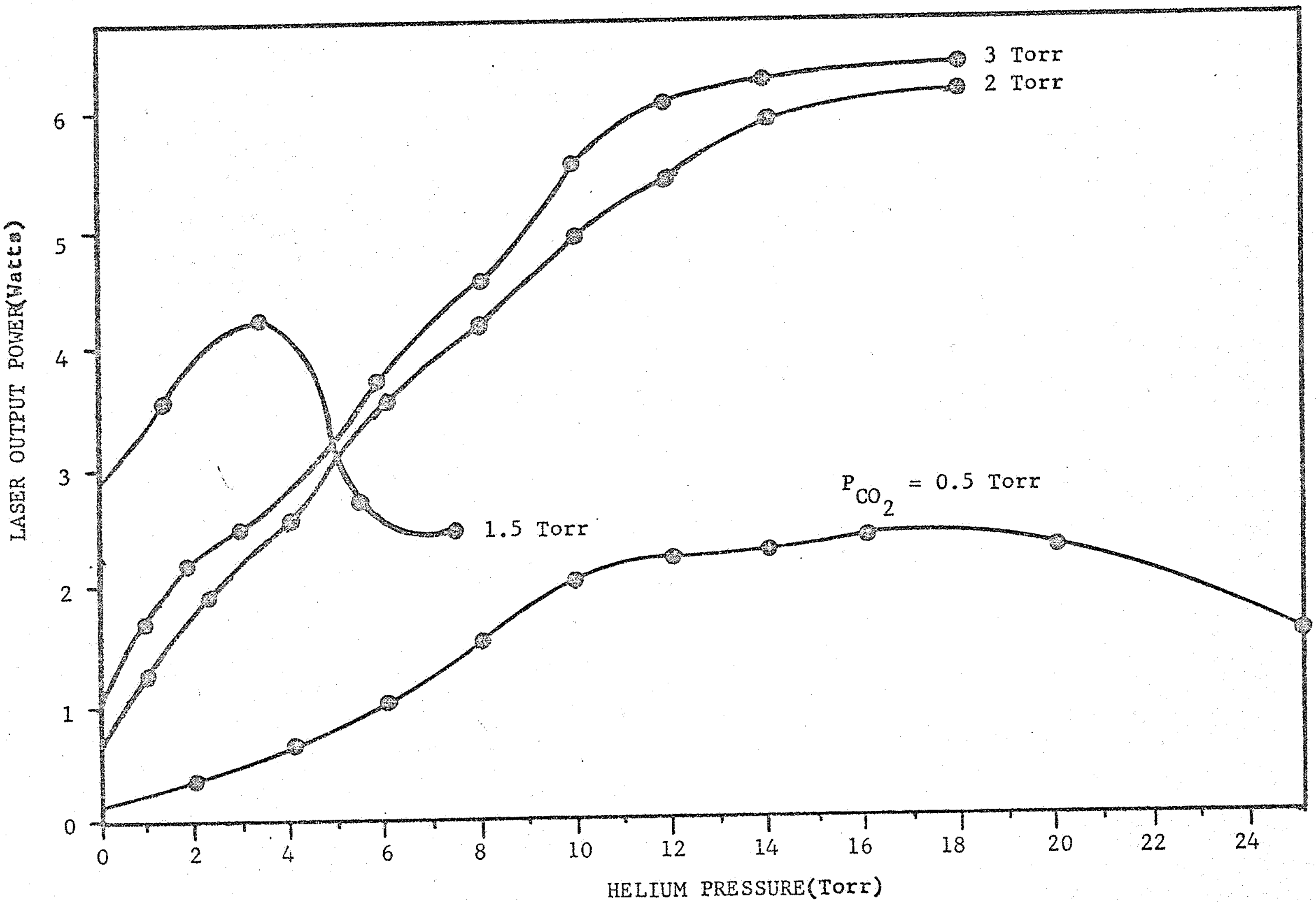

Figure 2. CO_2 Laser Output Power as a Function of Helium Partial Pressure for Various CO_2 Pressures

Clearing of the windows after the tube is turned off has been noticed, but the clearing is not complete, at least after a period of a few days. It appears that evacuating the tube allows some enhancement of the natural clearing rate. We also noticed that the rate of bluing was a function of the gas composition within the laser tube and without the existence of CO_2 the bluing rate was very slow.

Although chemical effects on the inside surface of the KCl could not be ruled out, it appeared more likely that color centers (F centers) were being formed in the KCl due to some electrical or optical phenomena. The generation of color centers in the alkali halide crystals is well documented in the literature and can be caused in a variety of ways. The crystals may be colored by the introduction of suitable chemical impurities which themselves exhibit color. Also, introducing an excess of the cation, as by heating in the vapor of the alkali metal can result in the generation of color centers. When sodium chloride is processed in this fashion* it exhibits a yellow color and potassium chloride exhibits a magenta color. It is also possible to color the crystals by x-ray and γ-ray radiation, neutron and electron bombardment and electrolysis.

Figure 3 shows the F band absorption for several alkali halides suitable for use as Brewster windows for 10.6 micron lasers. F bands introduced in KBr crystals should make the crystal appear light blue, due to its absorption in the red, NaCl should appear yellow, due to its absorption in the deep blue, and KCl should appear deep blue or magenta due to its absorption in the green and orange.

To verify that the coloring is the result of the formation of F centers, a discharge tube was fabricated with a KCl window on one end and a NaCl window on the other. The tube geometry is shown in Figure 4. Both windows were epoxied on to a pyrex tube 3/4 inch in diameter and 30 inches long. No cooling jacket was used. The tube was cleaned internally by running a discharge in He only for a short period of time. The tube was then filled with a typical lasing mixture

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* See C. Kittel, Introduction to Solid State Physics, 2nd Edition, pp. 492, (John Wiley & Sons, Inc., New York, 1956)

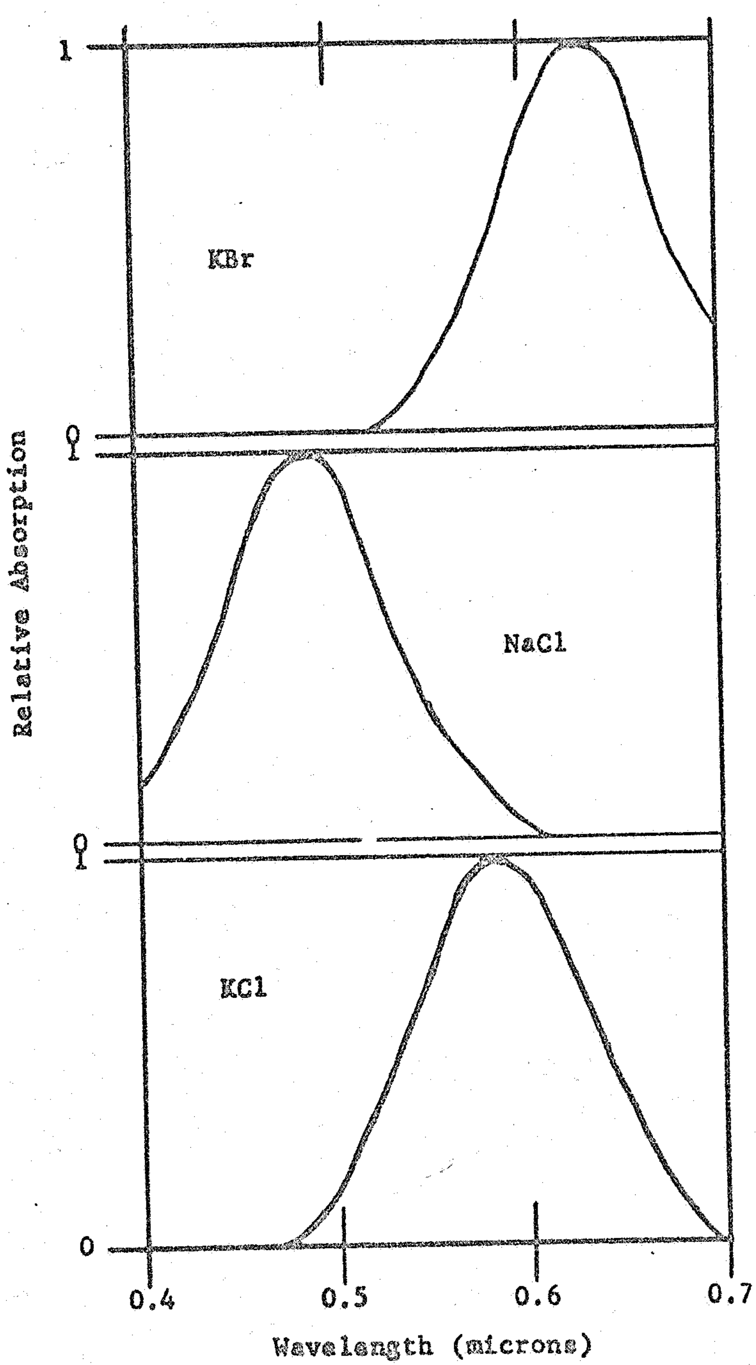

Figure 3 The F-Bands for Several Alkali Halides Useful as Brewster Angle Windows at 10.6 Microns. (Taken from Kittel)

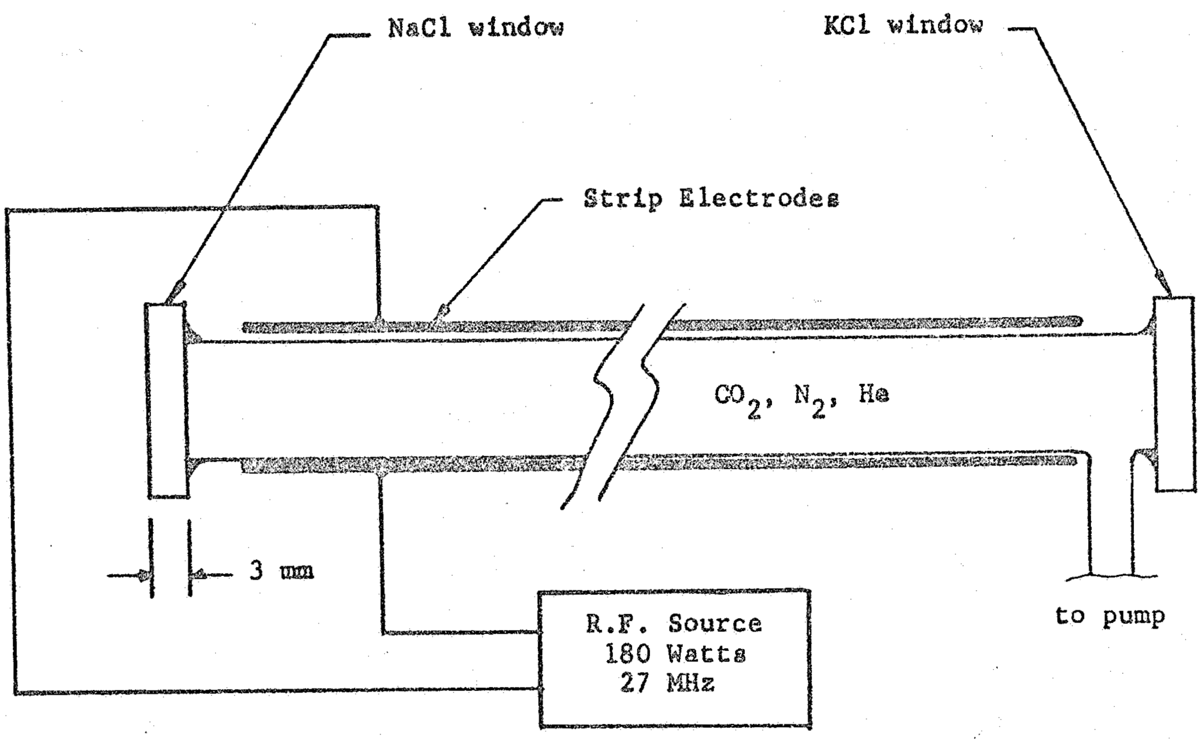

Figure 4. Experimental Demonstration of the Formation of F Bands in Alkali Halide Windows Used on CO_2 Laser Tubes

of CO_2, N_2 and He and operated for several hours. The KCl window turned a deep blue and the NaCl window turned a light yellow color. After 4 hours of operation, the KCl window exhibited deep coloring throughout its volume with the intensity fading from the inside toward the outside face. The region outside the extended bore diameter of the discharge tube remained clear. The tube was dismantled and a transmission curve was run on the KCl window. The absorption matched well the expected absorption curve due to color centers. However, the NaCl crystal faded in color too rapidly to obtain an absorption curve with enough definition to correlate it with the expected curve. Also, the color intensity in the NaCl never did reach the intensity of the KCl crystal and the coloring effect disappeared rather rapidly (several hours) compared to the KCl crystal.

It is felt that the generation of color centers is caused by the absorption of ultraviolet radiation being emitted by the discharge. The transmission characteristics of NaCl to ultraviolet radiation is much better than for KCl, which may explain the color intensity difference between the two. Although we have not yet tested KBr, we expect that the color intensity in this crystal will also be less than in KCl due to its better ultraviolet transmission characteristics. We expect to compare the color center formation characteristics and the hygroscopic characteristics of KBr with NaCl and KCl during the next quarter. Our experience has indicated that KCl has superior hygroscopic properties over NaCl.

To eliminate the possibility of electrical formation of the color centers, we fabricated a tube with long metal ends onto which the windows were attached. The tube was operated normally and with the ends grounded. No change in the rate of color formation was observed. Also, no effect was observed when high magnetic fields (approximately 400 gauss) were applied around the Brewster pipe. Apparently no electrical particles are bombarding the Brewster window, at least at high energies.

As expected, with the formation of color centers, the coloring could be prevented or removed by the application of heat from infrared heat lamps to the windows. Thermal deexcitation and/or bleaching with light in the F absorption band of the crystal can return the crystal to its normal state. It was observed that temperatures in the range of 65°C were required before the bluing effect in KCl could be completely eliminated. It may be possible that the heating of the oscillator cavities into which the lasers will be installed may impede the formation of color centers to the point that effect will not cause a substantial decrease in laser output power. Tests in this area will be made during the next quarter.

2.2.3 Lifetime Tests

During this period lifetime tests were made with two R.F. tubes and one d.c. operated tube. Neither of the R.F. tubes had any reservoir volume; the d.c. tube had a reservoir volume of approximately 1/2 liter which was about 5 times the active volume of the laser.

After processing and operating on the pumps for about two weeks, two R.F. excited CO_2 lasers were tipped off and installed in the cavities which were constructed during the previous quarter. One tube was operated almost immediately while the second tube was set aside for about ten days. The first tube was operated nearly continuously for a period of about 100 hours with little change in output power. The tube output rapidly dropped after the 100-hour period and reached the point of not lasing at about 135 hours.

Normally the CO_2 lasers we have processed have a whitish-blue discharge when they are operating well. When the tube failed, the color of the discharge was purple indicating an excess of nitrogen or a lack of CO_2.

The second tube was then operated; however, it only provided useful output for 20 hours. We believe that this tube suffered difficulty at the seal-off which created an unfavorable gas mixture within the tube. Both of the above tubes used a gas mixture of 2 torr CO_2, 1 torr N_2 and 9 torr He.

The d.c. operated tube was not removed from the vacuum system, but was valved off from the filling station by an ultra-high vacuum valve. The ballast volume for the tube was essentially the gas pumping line. This tube was filled with a mixture of 2 torr CO_2 and 8 torr He (no nitrogen) and was allowed to operate continuously. The power output remained constant for over 200 hours. At about 250 hours, one of the tube windows (KCl) cracked and the tube went up to atmospheric pressure. In the several hours before the tube failed, a slight decrease (25%) in output power was observed. The design of later d.c. tubes has been changed to eliminate the cause (thermal strain) of the cleaving windows. It is felt that with a reasonable size reservoir of about 1 liter, lifetimes near 500 hours should be expected.*

During this next quarter, various cathode materials will be tested and different window sealing materials will be tried. Also higher voltage power supplies will be used in order to operate at higher pressure gas fills. A larger supply of CO_2 may extend the lifetime without degrading power output as witnessed during the parametric studies mentioned earlier.

2.3 Laser Bore Size Effects

Several laser tubes were constructed during this quarter to determine if there existed an optimum size tube for the case when R.F. excitation is used. All of the tubes had identical lengths of 75 cm with an active plasma length of about 60 cm. Similar to the tubes described in the previous report, the bore sizes studied were 12, 19 and 27 mm in diameter in the plasma region. However, all the tubes were restricted to a 12 mm diameter optical size by an aperture, in order to compare their power output capabilities when operating near or in a single mode. The tubes were also equipped with internal cold cathode electrodes so that they could also be operated d.c.

Various combinations of gas pressures and mixtures were used in an attempt to optimize the power output. The tests were also run with various input powers up to 200 watts.

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* For a similar size tube as above, but not designed for high output power, W. Whitney of NRL, Washington has achieved over 1000 hours life with a CO_2:He mixture.

The results of these tests indicated a very clear preference in favor of the smaller diameter laser tubes. The large bore tubes, although capable of producing greater total output power were severely limited when apertured down to where they would operate in a single mode. With a 12 mm aperture the 27 mm diameter tube, for example, operated at a maximum power of about 1/2 watt. The 19 mm bore tube emitted about 1 watt and the 12 mm bore ran at about 2 watts.

For the tests conducted a 12 mm diameter aperture produced nearly a single-mode output as observed on a thermographic phosphor viewing screen of the type described by Bridges and Burkhardt.* As shown in Figure 5 the 27 mm diameter tube operated at the 1/2 watt level, the 19 mm tube at 1 watt and the 12 mm tube at 2 watts. It is not known whether the 8% transmission multilayer dielectric output mirror used in these tests was optimum for the tubes tested.

For the results obtained, a diameter dependent output for single mode or near single mode operation was seen to have a functional relationship of $\approx d^{-1.5}$, where d is the tube bore diameter. This functional relationship will of course, change when the tube size is reduced small enough that diffraction losses on the lowest order mode become large enough to severely limit the laser output power.

We were not able to obtain satisfactory results with the small bore tube when operated with R.F. excitation. A uniform discharge could not be obtained in the tube using parallel strip electrodes along the outside of the tube. This particular type of electrode geometry has proved most satisfactory for the larger bore tubes, but does not appear to be satisfactory for the smaller bore tubes. We were only able to obtain about 100 milliwatts from this tube using R.F. excitation while the same tube would provide over 2 watts with d.c. excitation.

Also for small tube geometries the characteristics of the R.F. discharge vary as the tube pressure is changed. For some pressure values, for example,

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* T. J. Bridges and E. G. Burkhardt, IEEE Journal of Quantum Electronics, QE-3, pp. 168, (April 1967).

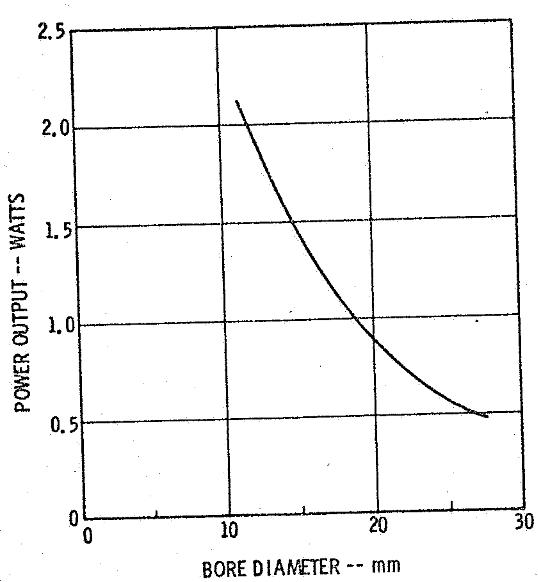

Figure 5. Near Single Mode Power Output as a Function of Bore Diameter

we were able to obtain a near null in discharge intensity at the center of the tube while a bright discharge occurred near the walls, making it very difficult to find the optimum operating conditions.

The various tests made this quarter have shown that:

(1) Small bore tubes are capable of providing greater single mode output power than large bore tubes,

(2) a degradation in laser output power from witholding N_2 from the tube may be less than 25% and

(3) lifetimes of over 250 hours appear possible in d.c. tubes when no N_2 is present in the tube.

Based on the above results, we have made the decision to construct the oscillators utilizing d.c. excitation and have ordered the appropriate d.c. power supplies. Also, as condluded in the next section, d.c. operation of the amplifiers now appears to have definite advantages over R.F. operation. Therefore, the entire laser system will be d.c. operated rather than R.F. and a change over to this mode of operation will be made during the next quarter.

2.4 Gain Studies for R.F. Driven Amplifier Tubes

Before the decision was made to operate the amplifiers with d.c. excitation, single-pass gain measurements were made this quarter utilizing a 2-meter long R.F.-excited amplifier tube. The tube utilized Brewster windows on both ends.

Because of the 2 meter length of the tube we had much difficulty in breaking down the tube at the 27 MHz frequency we had previously used for the smaller oscillator tubes. Since the electrical length of the amplifier tube was a substantial fraction of a half wave at 27 MHz, we were not able to maintain a uniformly high voltage along the full length of the strip electrodes used. However, by reducing the driving frequency to 13 MHz and rebuilding the matching networks we were able to drive the tube quite satisfactorily at a power level up to 500 watts input.

The bore diameter of the amplifier tube was 25 mm, however, only the central 10 mm diameter was used in the gain measurements. An oscillator which emitted up to 2.5 watts c.w. was used. The oscillator beam was passed through the amplifier tube, through a chopping wheel, a lens, and on to a gold-doped germanium detector. The gain was measured by turning the amplifier tube on and off.

The greatest gain figure observed for the tube was 1.67 for a 3 torr CO_2 and 8 torr He mixture. This corresponds to a gain figure of 28% per meter. At higher partial pressures of CO_2 the gain was reduced below this value. To establish whether any saturation effects were taking place, the oscillator power was reduced by a factor of two and the above gain measurements repeated. No saturation effects were observed.

Recently, gain measurements for both flowing* and non-flowing** CO_2 laser systems have been published in which d.c. operated tubes of varying bore diameters have been studied. For the flowing systems, high enough power densities from the oscillator were used to observe gain saturation effects. For the case of flowing CO_2:He:N_2, a saturation parameter of about 100 watts/cm^2 was observed.

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* H. Kogelnik and T. J. Bridges, "A Nonresonant Multipass CO_2 Laser Amplifier," IEEE Journal of Quantum Electronics, QE-3, pp. 95, (February 1967), and

T. F. Deutch, "Gain and Fluorescence Characteristics of Flowing CO_2 Laser Systems," IEEE Journal of Quantum Electronics, QE-3, pp. 151, (April 1967).

** P. K. Cheo and H. G. Cooper, "Gain Characteristics of CO_2 Laser Amplifiers at 10.6 Microns," IEEE Journal of Quantum Electronics, QE-3, pp. 79, (February 1967).

This parameter has not yet been measured for the non-flowing case, however, it may be of the same order of magnitude. Therefore, caution must be observed in the design of the optics so that near the final stages of amplification the beam diameter does not become too small. Further research in this area will be necessary before the saturation limitation can be fully described.

For the case of non-flowing systems, a gain of 40% per meter was observed for d.c. excited amplifiers. This value is significantly higher than in our case using R.F. excitation. Unfortunately, the tube we tested could not be operated d.c. and no comparative data could be taken. Moreover, the highest gain figure (40%) observed in the d.c. tubes occurred with only CO_2 and He mixtures (no N_2). With the greater lifetime characteristics in the discharge tubes observed with this gas mixture, it appears most desirable to operate the amplifiers in the 20-watt laser system we are constructing with d.c. excitation.

Therefore, the amplifier tubes for the laser system will be redesigned to operate with d.c. power. It is expected that each amplifier tube will require approximately 20 kv at 15 ma to operate at the optimum gain. Two power supplies with the above capability have been ordered and will be received during the next quarter.

2.5 Thermal Studies of the CO_2 Laser Cavity

During the past quarter, thermal stability measurements were made on the aluminum-invar laser cavities which were completed in the first quarter. These tests were performed with an active CO_2 laser mounted in the cavity and with the thermal stabilization network described in section 2.6 operating.

While the laser was operating the cavity allowed to come to equilibrium at room temperature, the long-term stability of the output was measured by passing the beam through a monochrometer onto a thermal detector.

In general, the output of the laser could only be kept on a particular wavelength for a period of a few minutes before the laser output would drift to a new wavelength. The apparent lack of good long-term stability did not seem consistent with expected results based on the cavity design.

The cavity was then heated by the thermal control system and the temperature rise of the cavity was observed as a function of time. Simultaneously, a calibrated piezoelectric stack, onto which one of the laser mirrors was attached, and a voltage variable d.c. voltage source, were used to maintain the same output wavelength from the laser. The absolute expansion rate was then obtained for the laser cavity.

It was discovered that the effective coefficient of expansion was about 10 times that of the invar rods to which the mirrors are attached. Several possible explanations were examined to determine the cause of the unexpected large thermal expansion coefficient of the cavity. The most reasonable explanation came out of an analysis, reproduced below, of the bonding technique used to hold the invar in the aluminum structural frame (see First Quarterly Report).

A "semi-rigid" aluminum based epoxy was used to hold the invar in the aluminum channel structure so that good thermal contact could be made between the aluminum and the invar. Apparently, the shear strength of the aluminum epoxy was great enough to somewhat pull the invar along with the aluminum channel as it expanded and contracted with thermal changes. This effect can be seen from the following analysis.

Refering to Figure 6a, assume that the aluminum and the invar have both thermal and elastic deformations, but the epoxy has only elastic deformation. This assumption greatly simplifies the calculations and, as can be seen at the end of the analysis, this assumption is quite good.

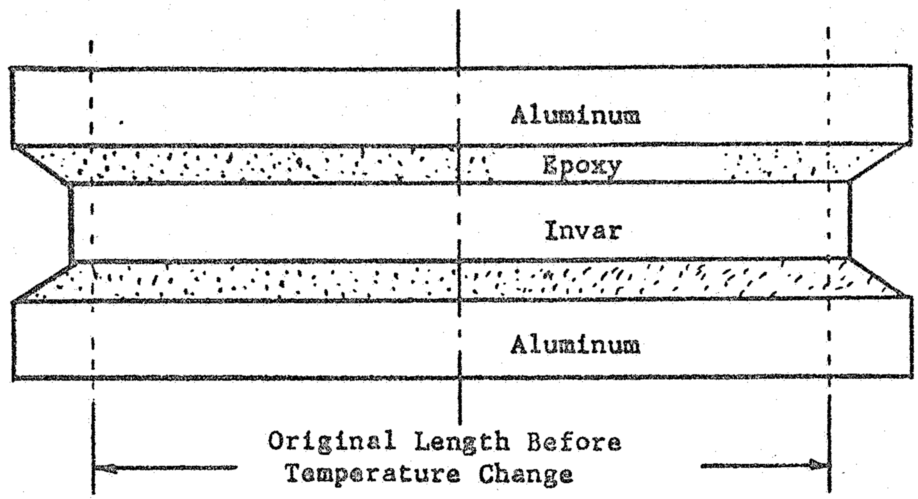


Figure 6a. Diagram of Aluminum Structure Holding Invar Rod with Epoxy

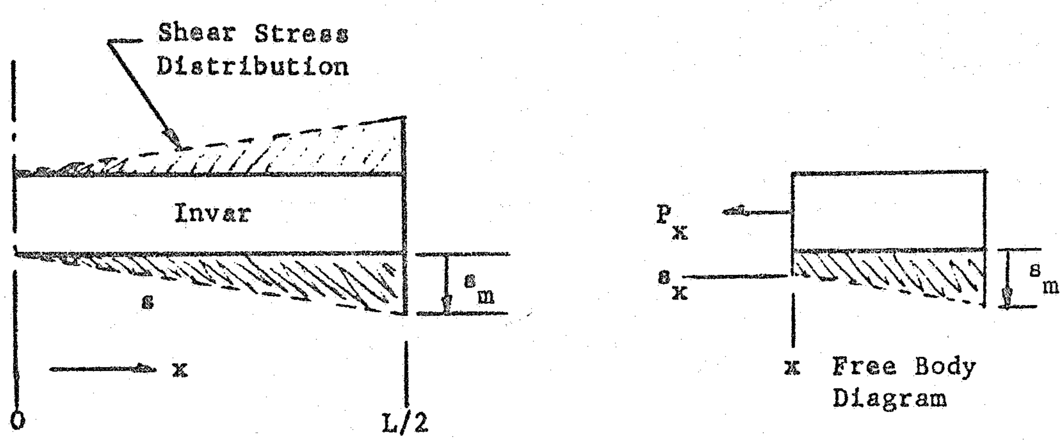


Figure 6b. Invar Rod with Distributed Stress

From geometry, the differential thermal (T) expansion between the invar and the aluminum must equal the sum of the elastic (E) deformations in the three materials.

$$(\Delta L_{Al})_T - (\Delta L_{In})_T = (\Delta L_{In})_E + (\Delta L_{Al})_E + (\Delta L_{Ep})_E \qquad (1)$$

The total expansion of the invar is the quantity of interest. It is given by

$$(\Delta L_{In}) = (\Delta L_{In})_T + (\Delta L_{In})_E \qquad (2)$$

and to obtain (ΔL_{In}) we need to determine each of the individual deformations. For the case when $L \approx L_{In} \approx L_{Ep} \approx L_{Al}$

$$(\Delta L_{In})_T = \alpha_{In} \; L \; \Delta \; T \qquad (3)$$

and $$(\Delta L_{Al})_T = \alpha_{Al} \; L \; \Delta \; T \qquad (4)$$

where α is the coefficient of thermal expansion at ΔT is the temperature rise of the material.

Considering the elastic deformation of the invar, the differential expansion between the aluminum and the invar will produce a shear stress in the epoxy which will increase linearity from the center of the structure to the ends. This stress can be expressed as a one dimensional distributed shear force, s , with dimensions of lb/in. The force will, of course, be assumed to act uniformly over the circumference of the invar at each position as depicted in Figure 6b.

Refering to the free body diagram in Figure 6b, the force acting on the invar at position x can be written as

$$P_x = \frac{1}{2} s_m \frac{L}{2} - \frac{1}{2} s_x x$$

$$= \left(\frac{1}{2} \frac{s_m L}{2} - \frac{2 s_m x^2}{L}\right)$$

and the elastic deformation Δ (dx) due to this force on an incremental length (dx) at x is given by

$$\Delta(dx) = \frac{P_x dx}{A_{In} E_{In}}$$

where A_{In} is the cross-sectional area of the invar and E_{In} is the modulus of elasticity of invar.

The total deformation for one half the length of invar will be the integral of the incremental values, and the total deformation will be twice the integral.

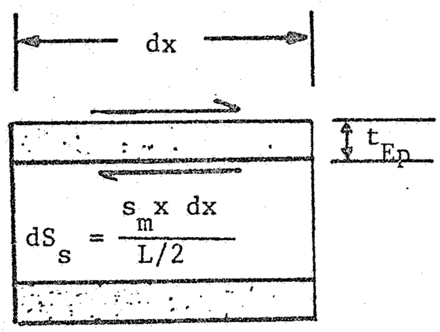
$$(\Delta L_{In})_E = 2 \int_0^{L/2} \frac{P_x dx}{A_{In} E_{In}}$$

$$(\Delta L_{In})_E = \frac{s_m L^2}{6 A_{In} E_{In}} \qquad (5)$$

Similarly for the aluminum

$$(\Delta L_{Al})_E = \frac{s_m L^2}{6 A_{Al} E_{Al}} \qquad (6)$$

Now to find the elastic deformation of the epoxy, consider an elemental ring of epoxy at position x with length dx. A cross section of this ring is shown below. Again the shear force is considered to be uniformly distributed from the center to each end of the epoxy joint and to act uniformly over the ring of epoxy.



The deformation across the epoxy due to the shear strain at position x is then

$$\Delta(dx) = \frac{t_{Ep}}{C\, G_{Ep}} \frac{dS_x}{dx} = \frac{2 s_m\, x\, t_{Ep}}{L\, C\, G_{Ep}}$$

where C is the circumference of the epoxy ring and G_{Ep} is the shear modulus of elasticity of the epoxy.

Note that the deformation of the epoxy increases linearly from the center to the end and that the total elastic deformation for the epoxy will be twice that at one end.

Since the area of the epoxy A_{Ep} , can be written $A_{Ep} = LC$ we can write for the maximum deformation which occurs at $x = L$ for the entire rod

$$(\Delta L_{Ep})_E = \frac{2\, s_m\, L\, t_{Ep}}{A_{Ep}\, G_{Ep}} \tag{7}$$

We now have all the relationships necessary to solve for ΔL_{In}. Substituting (3), (4), (5), (6) and (7) into equation (1) and solving for $s_m L$ we get

$$s_m L = \frac{(\alpha_{Al} - \alpha_{In}) \quad L \, \Delta \, T}{\dfrac{L}{6 \, A_{In} \, E_{In}} + \dfrac{L}{6 \, A_{Al} \, E_{Al}} + \dfrac{2 \, t_{Ep}}{A_{Ep} \, G_{Ep}}} \tag{8}$$

combining equation (8) with (3), (5) and (2) and arranging the terms, we get, finally

$$\boxed{\frac{1}{\Delta T} \left(\frac{\Delta L}{L}\right)_{In} = \alpha_{In} + \frac{(\alpha_{Al} - \alpha_{In})}{1 + \dfrac{A_{In} \, E_{In}}{A_{Al} \, E_{Al}} + 12 \, \dfrac{t_{Ep}}{L} \, \dfrac{A_{In} \, E_{In}}{A_{Ep} \, G_{Ep}}}} \tag{9}$$

which is the effective coefficient of expansion of the invar as it is pulled by the aluminum through the strength of the epoxy joint.

From a vibration viewpoint, it is most desirable to have the invar very tightly coupled to the aluminum structure. The rigidity and mass of the aluminum would tend to keep the resonant frequency of the overall mirror structure high. However, as seen from equation (9), when G_{Ep} is very large, the effective coefficient of expansion of the cavity approaches that of aluminum, which in this case would not be tolerable.

As an estimate of the magnitude of this effect, the following values apply:

$$\alpha_{In} = 1 \times 10^{-6}/^{o}C$$

$$E_{In} = 27 \times 10^{6} \text{ psi}$$

$$A_{In} = 0.614 \text{ in}^2$$

$$L = 39.4 \text{ inches}$$

$$\alpha_{Al} = 22 \times 10^{-6}/^{o}C$$

$$E_{Al} = 10.5 \times 10^{6} \text{ psi}$$

$$A_{Al} = 4.45 \text{ in}^{2}$$

$$A_{Ep} = 77 \text{ in}^{2}$$

$$t_{Ep} = 0.030 \text{ in}$$

and for a "hard" epoxy

$$G_{Ep} \simeq 0.25 \times 10^{6} \text{ psi}$$

evaluating equation (9) with these values gives

$$\frac{1}{\Delta T}\left(\frac{\Delta L}{L}\right)_{In} = 17 \times 10^{-6}/^{o}C$$

which is, of course, too large for our purposes. This expansion coefficient corresponds to a thermal stability of 500 MHz/^{o}C for a 1 meter laser cavity operating at 10 microns. To obtain the desired stability we need an effective coefficient of expansion of about 2 - 4 x $10^{-6}/^{o}C$ or less, and from equation (9), to obtain this value, the invar rods must be installed and held by an adhesive which exhibits a shear modulus, G , of less than about 200 psi.

This value of shear modulus falls almost into the "rubbery" range and very few materials, which may be useful for our purposes, have published values of G. To find a suitable materials we made a test jig which simply involved two metal cylinders, one inside the other, with a 0.030 inch annular gap between them. An adhesive to be tested was used to glue the two pieces together and after the adhesive had set, the unit was tested on a tensiometer. The following results were obtained.

Material	G (psi)
Hysol 0266 Epoxy	180
G.E. - RTV 30	120
G.E. - RTV 11	24
Semi-rigid E&C Aluminum Epoxy	> 3×10^4

The Emmerson and Cummings aluminum epoxy was used in the original fabrication. Its high shear modulus apparently accounts for the observed large thermal expansion coefficient.

As soon as we complete taking data on the short-term stability of the present cavities, they will be dismantled and the aluminum epoxy dissolved with a suitable epoxy solvent. The units will then be reassembled utilizing either the Hysol epoxy or the RTV 30 material.

2.6 Thermal Control System

In the last report a laser cavity temperature control circuit was presented which would be capable of monitoring the temperature of the laser cavity and maintain its temperature at an adjustable set point near 40-50°C to within $\pm$ 0.1°C. The circuit simply involved a bridge network which utilized a sensitive thermistor (thermal sensitive resistor) in one leg. The bridge network served as a proportional controller which regulated the current flowing through a heater wire attached over a large surface area of the laser cavity.

Fabrication of two units were completed this quarter. Figure 7 is a photograph of one of the units. The control electronics are mounted under the chassis

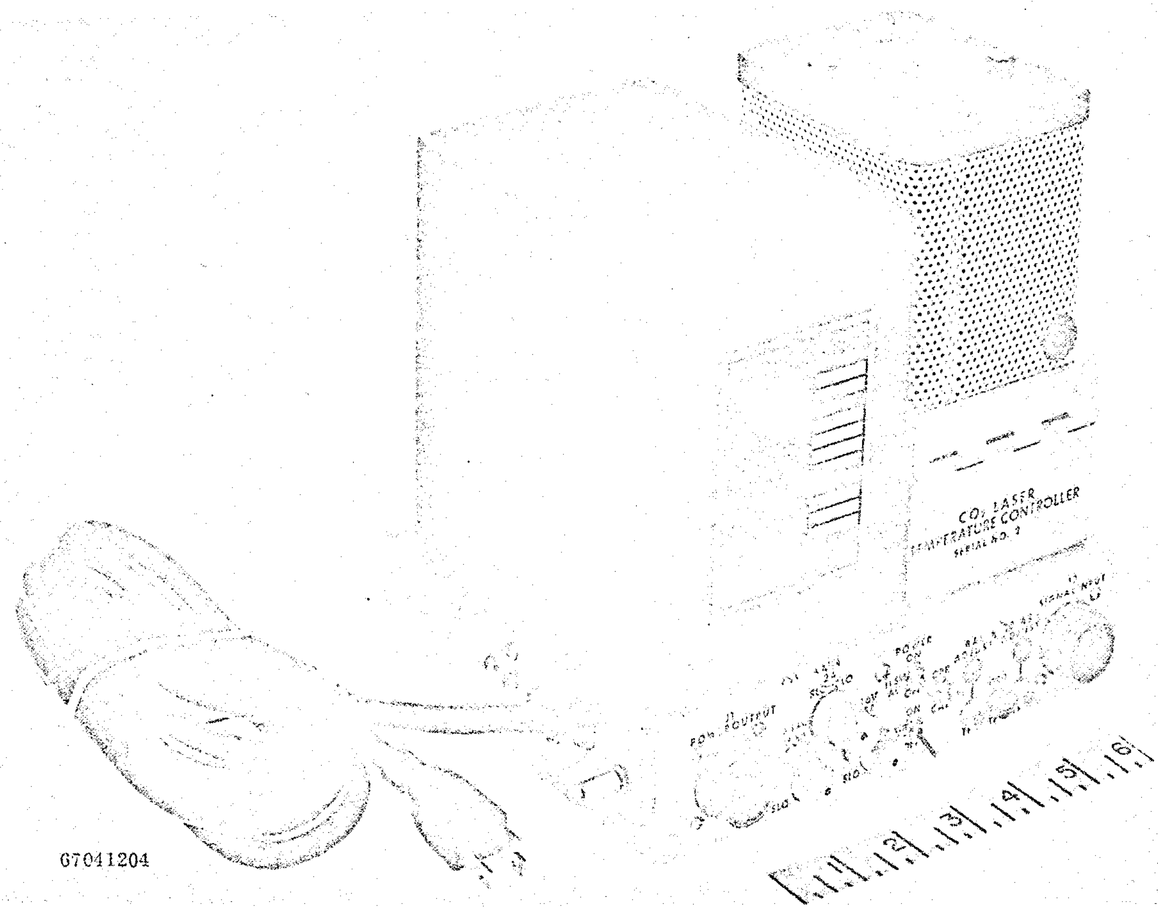


Figure 7. CO_2 Laser Temperature Controller

while two d.c. power supplies are mounted on top. The larger power supply provides 80 watts of d.c. power to the cavity heater. The smaller supply provides bias voltages to the integrated amplifiers used in the control loop.

The thermistor used in the control loop has the characteristics shown in Figure 8. This particular unit was chosen because of its high dR/dT near the desired operating temperature of $50^{\circ}C$. The thermistor is mounted on a miniature connector attached directly to the metal laser cavity.

The temperature controller is well fused and has all the necessary easy-to-reach components for accurate adjustment of the cavity temperature. The unit also has an auxiliary bias voltage output jack delivering $\pm$ 16 VDC and + 40 VDC with sufficient power to drive the AFC electronics which will be used while testing the stability of the lasers in a heterodyne mode of operation.

The units have been tested on the laser cavities and have been found to operate satisfactory.

2.7 Automatic Frequency Control Electronics

In order to measure the frequency stability characteristics of the 20-watt laser, heterodyne techniques must be used. Two laser cavities are being constructed so that their laser outputs can be heterodyned together. The technique for measuring the frequency stability of the lasers is shown in block diagram form in Figure 9. The low-power laser is heterodyned with the high-power laser. Part of the heterodyne signal is used to track out low-frequency drifts and variations which will not be noticed during the operation of the 20-watt laser in its final position. Since during actual operation the round trip period of the 20-watt laser beam is expected to be no greater than 10 milliseconds, the AFC loop can safely track out frequency variations between the tests lasers which occur at rates less than about 100 Hz. Since the AFC loop will tend to compensate for the slow frequency drifts in the output of both lasers, the short-term stability can be accurately determined with the use of a suitable spectrum analyzer or wave analyzer.

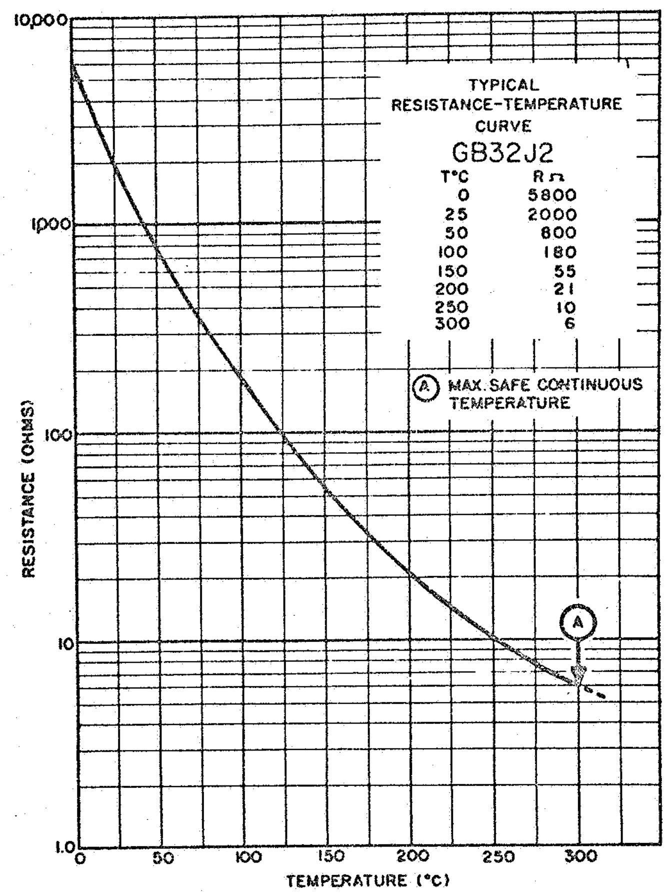


Figure 8. Thermal Characteristic of the Thermistor Used in the Laser Temperature Control Electronics

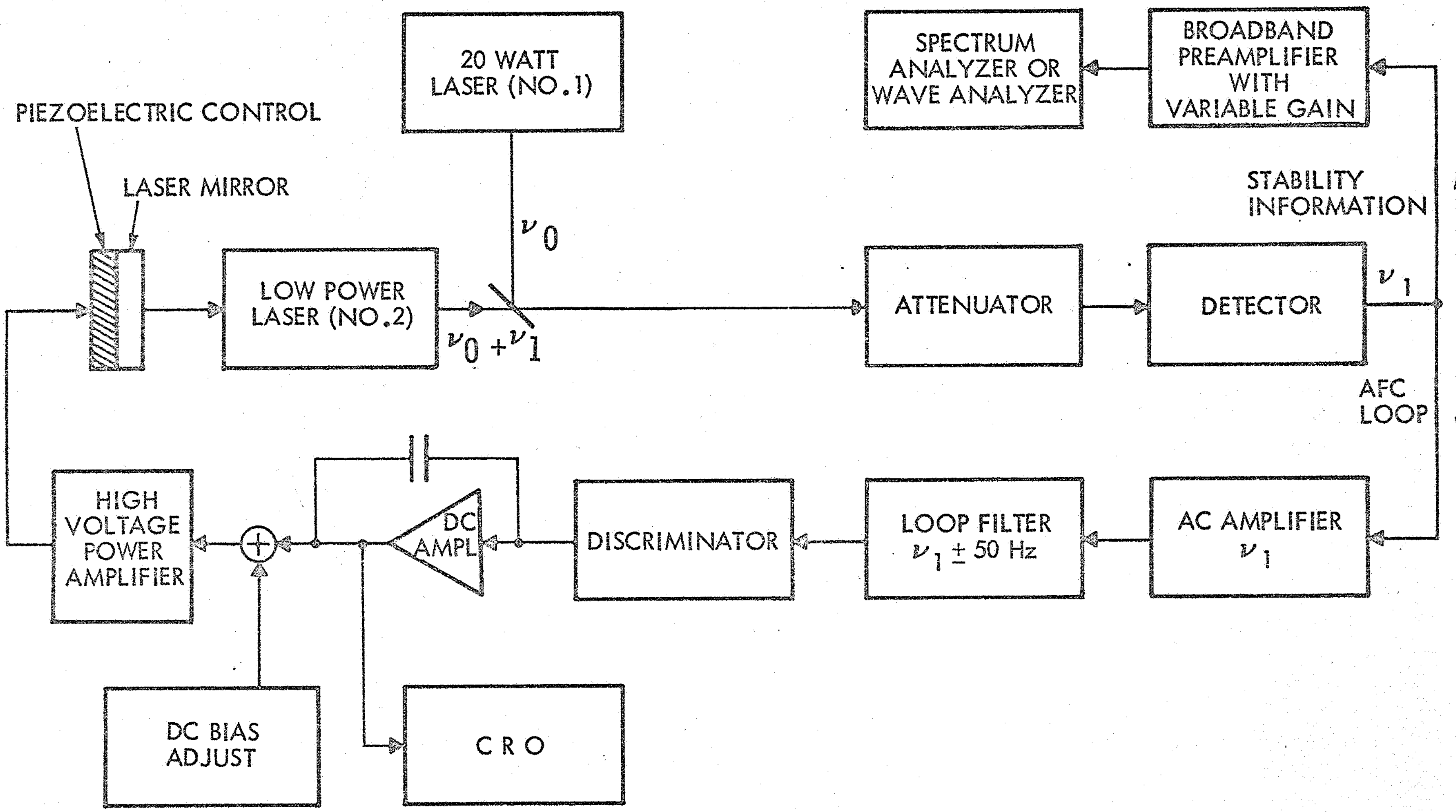


Figure 9. Technique for Measuring Long-and Short-Term Laser Frequency Stability

The details of the design of the AFC loop were determined during the last quarter and fabrication of the unit was completed this quarter.

The difference frequency (chosen to be 1 MHz) is generated in the detector and passed through the low level bandpass video amplifier. The bandpass amplifier has a maximum gain of 2000 = 66 db and a gain adjust to compensate for different laser operating powers. The output of the amplifier is then fed to a discriminate with a $\pm$ 1 KHz bandwidth around 1 MHz with a maximum output voltage of 0.25 volts d.c. The circuit diagram for these units is shown in Figure 10.

The input circuit is a.c. coupled, and the tuning circuit provides parallel resonance at 1 MHz. The input circuit has a bandwidth of 200 KHz, giving a compromise between phase shift introduced around 1 MHz and elimination of broadband noise. A narrow bandwidth would more effectively eliminate undesired noise, but would introduce more phase shift in the AFC loop.

The first stage of amplification consists of a low noise FET cascode configuration. This configuration was chosen for its relatively high input impedance, its low noise characteristics, and its reduction of the Miller feedback effect in the cascode arrangement. This stage provides approximately 13 db of gain with a 180 degree phase reversal.

The second stage of amplification is provided by a common emitter configuration with the emitter capacitor being used to provide lead compensation at the stage output. This stage also provides approximately 13 db of gain with 180° phase reversal.

The third stage is an emitter follower with a gain control adjustment. This stage is required in order to reduce the source impedance as seen by the following Amelco video amplifier since the input impedance of the 901CE is about 500 ohms. This fourth stage provides about 20 db of amplification and C17 provides some required lag compensation.

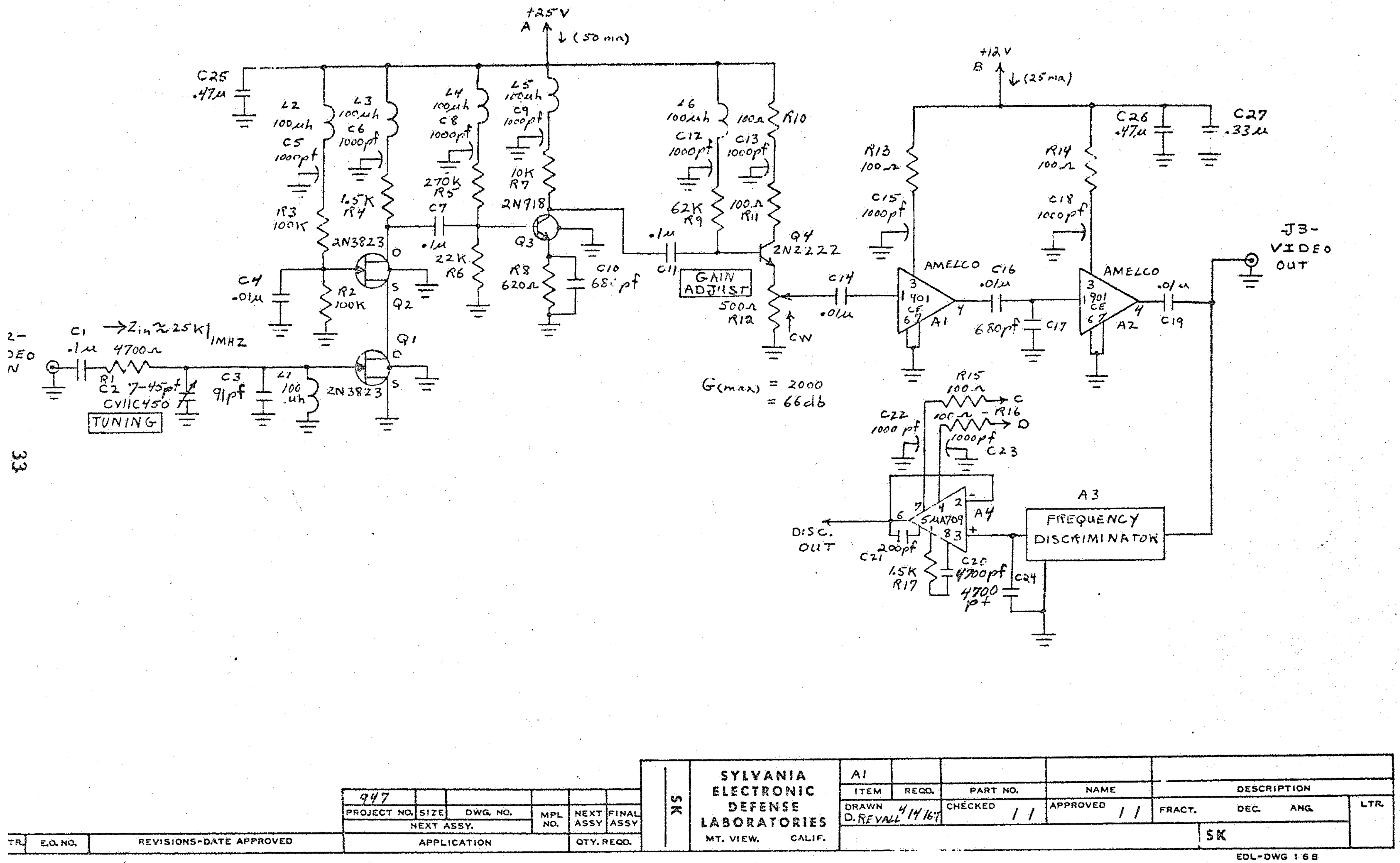


Figure 10. AFC Video Amplifier and Frequency Discriminator

The last stage provides another 20 db of amplification for a total video gain of 66 db maximum. It will be noted that no phase reversal exists from input to output for the individual Amelco stages since each stage consists of two direct coupled inverting amplifiers.

In practice, the only adjustment required for the video amplifier is to modify the gain control such that the output of the last stage (video out) is 1V RMS, the required rating for the frequency discriminator. All phase and tuning adjustments have been previously set.

Figure 11 shows the d.c. control section of the AFC loop with the components from Figure 10 shown as subassembly A1.

The discriminator output is fed into a combined integrator and high pass amplifier making the loop a type I system (zero d.c. error). The high pass amplifier is used to compensate for the low pass characteristics of the high voltage programable supply with the piezoelectric stack. This is necessary in order to increase the closed loop bandwidth to 100 Hz.

Since the output impedance of the discriminator is quite high (100 KΩ), a voltage follower circuit is introduced to bring the output impedance down to an acceptable level. Capacitor C24 provides low pass filtering in order to eliminate 1 MHz frequency components that do exist at the open circuit output of the discriminator.

The high voltage supply available through J4 is programmed so as to provide a zero to 800 volt output excursion across the piezoelectric stack. This provides a safe operating level for the transducer. A nominal DC bias of 400 volts is to be placed across the transducer via the Coarse and Fine Bias Adjust pots shown in Figure 12 (TP1 being at 5 volts). These bias adjust pots perform a second function by providing the ability to change the transducer length manually when S2 is in the Manual position.

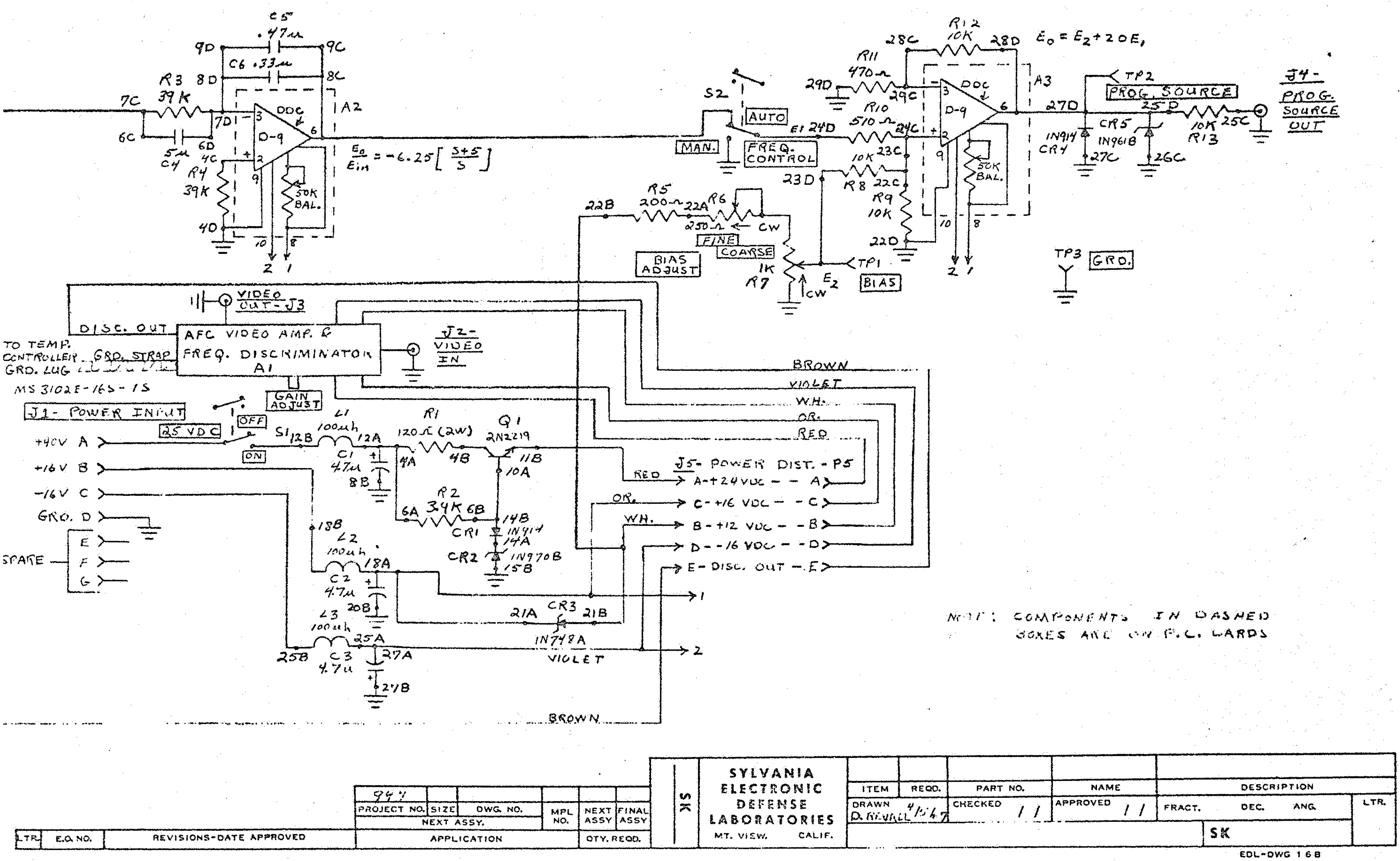


Figure 11. Circuit Diagram of the D.C. Control Section for the Laser AFC Loop

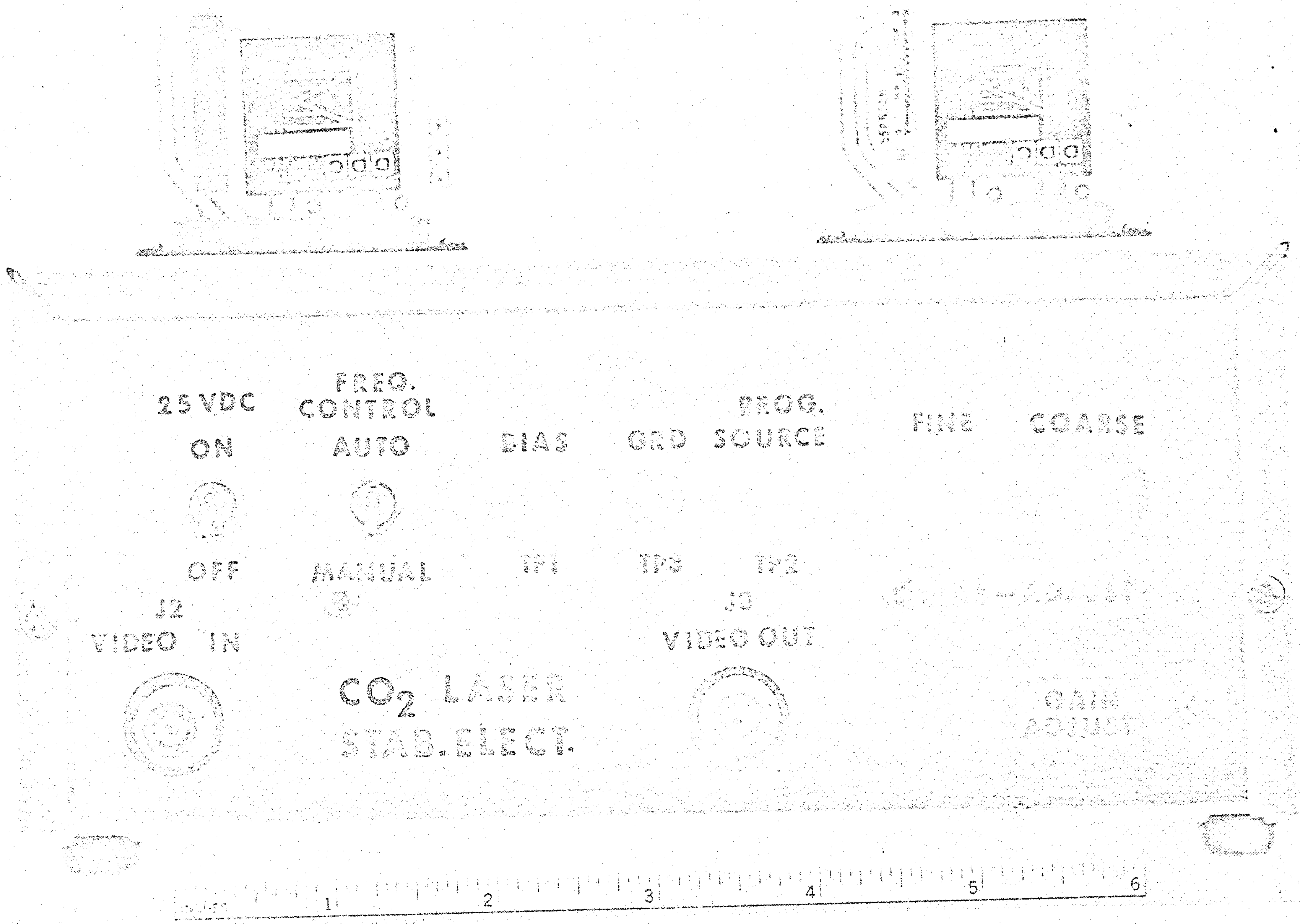


Figure 12. CO_2 Laser AFC Loop Electronics

The two stages of amplification following the discriminator raise the voltage to the required 10V for operation of the programable H.V. power supply (KEPCO 1000 ABCM, not shown).

Figure 12 is a photograph of the completed unit. Electrical tests have been completed on the unit, however, it has not yet been tested in the laser system.

The detector assembly which will be used with the AFC loop has also been completed. A gold-doped germanium detector with all the necessary bias equipment (battery operated) is enclosed in a metal box for R.F.I. shielding purposes. We have used the detector to view transverse mode beats from a CO_2 laser up to frequencies in the 40-50 MHz range. It is expected that the AFC loop will be used during the next quarter to study the short-term stability characteristics of the laser oscillators.

3.0 SUMMARY AND CONCLUSIONS

During this past quarter, we have completed the design and fabricated the major enclosure parts of the 20-watt CO_2 laser which consists of an oscillator operating at about 5 watts single mode and a 6 db CO_2 amplifier system. The mechanical enclosure for the system also serves as an acoustical isolator meant to reduce frequency instabilities due to vibrational effects and as a thermalizing shield to help maintain a constant temperature and dry atmosphere with the laser. Parametric studies on R.F. driven tubes have indicated that for maximum power output (multimode) an optimum CO_2-He mixture consists of a large partial pressure of CO_2. Ratios of 3 torr CO_2 to over 20 torr He appeared to be near optimum, however, higher pressures of both components may indeed provide higher output power, providing the power supply is available to operate the tube.

Measurements on the single pass gain of an R.F. excited CO_2 amplifier tube yielded gain figures of about 28% per meter, a somewhat lower figure than that reported for d.c. operated tubes. No saturation effects were observed for amplifier input power densities of up to 3.5 watts/cm^2. However, at the higher powers associated with the final stages of gain in the amplifiers, some saturation effects may be incurred if the beam size is not kept larger than about 1/2 cm in diameter.

Tests made on laser output power as a function of bore diameter for the case where the lasers were forced to operate in a single mode or near single mode indicated that small bore tubes provide a much greater output than large bore tubes. An emperical relation indicating that $P_{out} \propto d^{-1.5}$ was observed for the tubes tested.

Lifetime tests on several, both d.c. and R.F. excited, have indicated that lifetimes greater than 250 hours should be possible with d.c. excited tubes using gas mixtures containing only CO_2 and He. The results of all of the above tests and from published information on the gain characteristics of d.c. driven amplifier tubes utilizing CO_2-He mixtures has led us to conclude that an advantage can be realized in the overall laser system if d.c. excitation of the discharge tubes is used throughout. This is a major change in the original direction of the program where R.F. excitation was to be used in order to achieve long operating lifetimes.

Thermal studies of the laser cavities have indicated that the expansion rate of the invar rods used in the design was being influenced by the rest of the structure to a greater degree than anticipated. A thermal analysis of the system has indicated that a different bonding technique must be used to hold the invar within the aluminum support channel. The existing cavity structures will be repaired by dissolving the existing adhesive and substituting it with an appropriate adhesive with a much lower shear modulus of elasticity.

The temperature control units and the automatic frequency control electronics were completed this period. The AFC loop will be used in the short-term frequency stability tests during the next period. Two lasers will be locked to a difference frequency of 1 MHz and kept at that frequency by the AFC loop.

4.0 PLANS FOR THE NEXT PERIOD

The following outline indicates the areas to be pursued during the next quarter.

(1) construct the final 6 db amplifier package

(2) construct the final oscillator tubes

(3) order remaining power supply components and enclosures and begin component installation

(4) design and start fabrication of heat exchanger unit to be used with the 20-watt laser system

(5) perform both long-and short-term stability measurements

(6) continue life tests on CO_2 oscillators